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Repetitively Pulsed
CO_2 Laser-Target Interaction

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Raymond L. Loiselle, Lt. Col., USAF
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REPETITIVELY PULSED CO_2 LASER-TARGET INTERACTION

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PROJECT REPORT LTP-34

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ABSTRACT

Thermal coupling of CO_2 laser energy to metal surfaces of aluminum, titanium, stainless steel and copper has been measured under large-spot, repetitively pulsed conditions using the AVCO Humdinger, Sr., laser. Coupling measurements were made both at atmospheric pressure with a Mach 0.4 air flow transverse to the target surface and in a low-pressure environment of ~ 3 torr. An enhancement over cw coupling values was observed for the aluminum and stainless steel targets near the threshold for surface-plasma ignition. After passing through a maximum, the coupling decreased with increasing fluence and approached the cw value in the range of 40-50 J/cm^2. For the titanium targets, no enhancement over accepted cw values was observed. The multipulse coupling measured with Humdinger, Sr., is consistently less than previous measurements of single-pulse and small-spot multipulse coupling measured at other laser facilities. Time-resolved measurements of the energy deposition appear to indicate that the observed differences in the various sets of coupling data may be due to pulse shape effects.

The results of measurements of the damage to an aluminum structural member and of the ablation rates for Plexiglas and fused silica are also reported.

CONTENTS

REPETITIVELY PULSED CO_2 LASER-TARGET INTERACTIONS

I. INTRODUCTION

This report presents the results of a series of surface effects experiments which were conducted using the repetitively pulsed AVCO Humdinger, Sr., CO_2 laser. The experimental series included measurements of a) the average thermal coupling to rear-surface thermocoupled targets of aluminum, titanium, and stainless steel, b) time-resolved thermal coupling using front-surface thermocoupled copper targets, c) surface damage and ablative effects to the above metals and, in addition, dielectric targets of fused silica and plexiglas, and d) damage to an aluminum structural member.

The principal objective of the experiments was to investigate enhanced thermal coupling to metals under large-spot, repetitively pulsed conditions. Recent, small-spot thermal coupling measurements[1-4] have shown that if the incident laser intensity is sufficient to ignite an air-breakdown plasma at the target surface, the coupling of the laser energy into the target is increased by as much as an order of magnitude for highly reflective metals such as aluminum. It was found,[3,4] however, that for such small spots (area $\approx 0.03\ \text{cm}^2$) most of the energy is transferred by the expanding plasma to the target outside of the focal spot and is therefore of little benefit in reducing the time to reach surface melt temperature. Little enhancement of the absorbed energy fluence within the small focal spot was observed.[3,4] More recent large spot (area = 6-20 cm^2), single-pulse measurements[4,5] have shown that as the irradiated spot size was increased, the fraction of energy deposited by the expanding plasma that remained within the focal area increased, and definite

fluence coupling enhancement was observed. The purpose of the series of thermal coupling measurements reported here was to determine if this large-spot fluence-coupling enhancement is retained under repetitively pulsed conditions.

II. EXPERIMENT

The average thermal coupling to 2024-T3 aluminum, 6Al-4V titanium and type 304 stainless steel was measured using rear-surface thermocoupled targets. The 1/16 inch thick x 2 in. square targets were embedded in a low-thermal conductivity epoxy to minimize heat loss to the surroundings. The absorbed laser energy was calculated from the equilibrated temperature rise of a target as measured by two chromel-alumel thermocouples, one mounted at the center and the other at the outer edge of the rear surface of the target. The irradiated surfaces were in as-received condition with the exception of an alcohol cleaning to remove grease and surface contaminants.

Time-resolved thermal coupling was measured using front-surface thermocoupled copper targets. These targets consisted of a linear array of six copper-constantan surface thermocouples spaced approximately 3 mm apart and mounted in a copper block. The construction details of the targets and the analysis techniques for determining the time dependence of the absorbed energy are discussed in detail in Reference 4.

Measurements were made at two pulse repetition rates, 10 and 50 pps; two pressure conditions, ambient atmosphere and a low-pressure measurement at $\approx$3 torr; at pulse powers ranging from $\approx$1 MW/cm^2 to 3.5 MW/cm^2; and with the exception of the low-pressure measurements, with a Mach 0.4 transverse

air flow across the irradiated surface.

The experimental arrangement used is shown in Figure 1. The targets were mounted in the neck of a wind tunnel such that the air flow was transverse to the beam propagation direction. The 10 x 10 cm^2 laser beam was directed to the target through a propagation tank which, for the ambient atmosphere measurements, was pumped out and backfilled with high-purity nitrogen gas to minimize thermal blooming of the focussed beam. For the vacuum measurements, the propagation tank entrance was closed off with a salt window, the target area enclosed in a vacuum cube, and the entire system evacuated. The target was located in the geometric-beam region 15 meters downrange of a 22 meter focal length, water-cooled copper mirror.

Beam diagnostics for the measurements consisted of a) an RdF calorimeter to measure the total pulse train energy, b) a photon drag detector to monitor the pulse shape, and c) a $BaTiO_3$ detector to measure the individual pulse energy. The RdF calorimeter was calibrated to energy delivered at the target by a comparison to a second calorimeter placed at the target position. Prior to the experimental series, the spatial-energy distribution of the beam at the target position was measured using a 64-element pyroelectric array. An example of the results of the energy distribution measurements is shown in Figure 2 which shows the energy profiles of selected individual pulses of a 50-pulse train. Variations of a factor of two are observed to occur for both the spatial distribution within a given pulse and, at a given position, from pulse to pulse. As indicated in Figure 3, the beam profile when averaged over a pulse train reasonably approximated a flat-top distribution over a rectan-

gular spot with full width at half maximum dimensions of (30±3) x (33±3) mm^2. For the data analyses, the beam was taken to be a top-hat distribution with the above dimensions.

Diagnostics in the target area included a photodiode and open-shutter photography to monitor the ignition of breakdown plasmas at the target surface. Dirty-air breakdown in the final beam propagation region was also monitored using photodiodes and open-shutter photography. The latter was found to occur only at the higher fluences; by noting the number of occurrences and using known limits of the radial expansion velocity of the plasmas after ignition[6], the effect of the dirty-air breakdown on the energy transmission to the target was estimated and found to be significant only at the highest energy fluences used.

III. RESULTS

A. Thermal Coupling Measurements

The results of the average thermal coupling measurements for the aluminum targets at ambient atmospheric pressure are shown in Figure 4. The solid curve drawn through the data points is for convenience of viewing only and does not represent a theoretical fit to the data. Several important features are to be noted.

In order to compare these data to previous experimental results, the points plotted are the values of the average thermal coupling coefficient that would result if surface plasmas were ignited by each pulse in the pulse train. The measured value of the coupling coefficient, α_M, is calculated using the relation

$$\alpha_M = \frac{m\, C_p\, \Delta T}{E_T}$$

where m is the mass of the target, C_p, is the heat capacity, E_T is the total pulse train energy incident onto the target, and ΔT is the equilibrated temperature change of the target as measured by the rear-surface thermocouples. For those cases near the threshold for plasma ignition in which surface plasmas were not ignited by each laser pulse in the pulse train, the value of the plasma-enhancement factor can be calculated using the linear interpolation technique of Rudder[1] from the relation

$$\alpha_M = \alpha_o \varepsilon \frac{N_p}{N_t} + \alpha_o \left(1 - \frac{N_P}{N_T}\right)$$

where α_o is the cw coupling coefficient or the intrinsic absorptivity of the target material, ε is the plasma enhancement factor, N_T is the total number of pulses in the pulse train, and N_p is the number of pulses which ignited surface plasmas at the target. The quantities α_M and N_p are measured quantities and α_o is taken to be 0.03 (Reference 7); given these values, the plasma-enhancement factor can then be calculated. In Figure 4, the plotted data points for $10 \lesssim E/A \lesssim 13$ J/cm^2 represent the value of $\varepsilon\alpha_o$; for fluences greater than approximately 13 J/cm^2, surface plasmas were ignited by each laser pulse, and the plotted data points represent actual measured values of α_M.

At a peak threshold intensity of $\simeq$ 2.8 MW/cm^2, (taking into account both the gain-switched spike and spatial-energy variations) plasma enhancement was observed in which the coupling increased sharply above the cw value of ~ 3%, passed through a maximum, and then approached the cw value at an average energy fluence of $\approx$ 50 J/cm^2. At the high fluences, the skewed "error

bars" are intended to reflect the maximum effect that the dirty-air breakdown would have on the computed value of the coupling coefficient. It is estimated that, for $E/A \sim 48\ J/cm^2$, a maximum of 50% of the incident energy would be shielded from the surface by the observed air breakdown so that the measured coupling coefficient is, at most, a factor of two below its air-breakdown-free value. The shielding effect decreases with intensity as $I^{5/2}$, so that the air breakdown had no significant effect for fluences below $\sim 30\ J/cm^2$.

The dashed curve in Figure 4 represents the single-pulse results obtained by S. Marcus using the Lincoln Laboratory 500 J laser.[4] These data show a much sharper threshold and yield a value of the coupling coefficient which is consistently greater than the values measured with Humdinger, Sr. Near threshold, a comparison of the two sets of data cannot be made with confidence. The surfaces of the targets used in the single-pulse experiments were "roughened" with an abrasive before each laser shot to ensure the ignition of a uniform plasma in each case. The targets used in the Humdinger experiments were, as mentioned previously, in as-received condition so that, near threshold, the surface plasmas would not necessarily be as uniform and as well-developed as for the case of the single-pulse measurements. Furthermore, one would expect a "clean-up" effect in the multiple-pulse case in which the initial pulses would reduce the number of initiation sites thereby increasing the plasma threshold somewhat for succeeding pulses. Well above threshold, however, a well-formed plasma is ignited by each pulse independent of surface conditions and a comparison of the two sets of data is valid.

At the higher fluences, the multipulse coupling measured with Humdinger, Sr., is still less than the single-pulse values measured with the Lincoln laser. This raises the important question of whether multiple pulses intrinsically yield a lower enhanced coupling than a single pulse, or whether there are other factors such as pulse shape which are responsible for the observed differences. The small-spot, repetitively pulsed measurements carried out by Rudder on the AFWL laser[1] yielded values of the coupling coefficient which, in magnitude, agree well with the single-pulse results of Marcus. This comparison implies that the multipulse coupling is not intrinsically smaller than single-pulse coupling. As discussed below, there are indications that differences in the pulse shape of the two lasers may have an important effect on the measured values of the coupling coefficient.

From measurements of the time-resolved thermal coupling using front-surface thermocoupled aluminum targets, Marcus[4,5] found indications that the coupling was most efficient in the first few microseconds of the incident laser pulse while the plasma is still relatively close to the target surface. A comparison of the pulse shapes of the Lincoln Laboratory 500 Joule stable resonator laser as used by Marcus and the Humdinger, Sr., laser is shown in Figure 5. The energy content in the first three μsec of the Lincoln Laboratory laser is ~ 50% of the total pulse energy as compared to ~ 30% for Humdinger, Sr. This suggests that, if in fact the energy transfer from the plasma to the surface is most effective during the initial portion of the laser pulse, the Lincoln Laboratory pulse shape should yield a higher value of coupling coefficient at a given energy fluence. The differences in pulse shape may,

therefore, account for the uniformly greater single-pulse coupling. Additional evidence that this may be the case is provided by the results of the time-resolved coupling measurements on the front-surface thermocoupled targets shown in Figure 6. This figure shows the variation of the change of the surface temperature and the absorbed energy flux as a function of time for high and low fluences. The absorbed energy curves both peak in times less than 5 μsec. In particular, the high-fluence curve falls off very rapidly showing strong decoupling effects. An implication here is that, so long as the LSD threshold is not exceeded, a more optimal pulse shape to maximize coupling to the surface may be a shorter pulse which will transfer most of its energy to the plasma before significant decoupling occurs. Note that this implies that both pulse shape and pulse length are important.

The results of the low-pressure thermal coupling measurements for aluminum are shown in Figure 7 with the single-pulse results of Marcus plotted for comparison. As with the ambient atmosphere measurements, the multipulse coupling is less than the single-pulse result; however, in addition to possible influences of pulse shape, the differences in pressure may be contributing to the differences of the magnitude of the coupling coefficients. Marcus found that the low-pressure coupling did not increase significantly over atmospheric values unless very low pressures were attained.

The results of the titanium measurements are shown in Figure 8. The range of the values for the cw coupling quoted by Schriempf[7] is shown for reference. Although, at low fluences, the coupling was found to increase with the formation of a surface plasma, no enhancement over the quoted range of cw

values was observed. At high fluences, the pulsed coupling fell below the cw values as the plasma decoupled from the surface. As was the case for aluminum, the multipulse coupling is consistently less than the single-pulse values measured by Marcus indicating the possibility of pulse-shape effects. In this case, the surfaces of the targets used in both experiments were in as-received condition so that a direct comparison of the two sets of data is valid over the full range of fluence. The low-pressure titanium results are also shown in Figure 8. The curve connecting the three low-pressure data points is for viewing convenience only, and its shape has no physical significance.

The results of the stainless steel measurements are shown in Figure 9. With the ignition of a surface plasma, the pulsed coupling shows an initial enhancement over cw coupling and then falls below the cw values at fluences of 40 - 50 J/cm^2. The low-pressure data are also shown and connected with a straight line for viewing purposes.

B. Surface Damage - Metals

There was little surface damage observed for any of the 1/16 inch thick metal targets at the total integrated fluences used in the measurements. A 50-pulse pulse train was used for the measurements in air and a 10-pulse pulse train for the low-pressure experiments which yielded maximum integrated fluences of $\sim 2.5\ kJ/cm^2$ and $\sim 0.4\ kJ/cm^2$, respectively. (The possibility of damage to the salt windows limited the total fluences in the low-pressure measurements.)

In air at the lower fluences above the plasma threshold, varying degrees of surface melt and re-solidification were typically observed for all

three metals with aluminum exhibiting the least damage. At the higher fluences, there was usually little evidence of surface melt although the titanium and stainless steel targets showed considerable discoloration due to oxidation. At an ambient pressure of 3 torr, surface melt was observed for all the metals at both high and low fluences. There was no measurable mass loss (to within 0.1 g) for any of the 1/16 inch thick targets.

The damage produced in a structural member is shown in Figures 10 and 11. The structure was fabricated with a 0.016 inch thick 2024-T3 aluminum skin riveted to an aluminum frame. The construction details were similar to those used in aircraft construction. As shown in Figures 10 and 11, a hole was burned/punched through the skin of the structure in 50 and 58 pulses for transverse air flows of Mach 0.4 and 0.9, respectively. The repetition rate used in both cases was 100 pps and the average fluence per pulse was $\sim 58\ J/cm^2$. At these fluences, the measured coupling coefficient was approximately the cw value of 3%. The size of the hole shown in the photographs is approximately 25 x 30 mm or about the size of the incident beam.

Examination of the damaged areas indicated that the pulsed damage was thermo-mechanical in nature with apparently a thermally-induced weakening of the material and an impulse-induced breaking and tearing of the skin which was aided by the transverse air flow. Evidence of this is indicated by the jagged edges and cracks at the edges of the holes shown in Figures 10 and 11.

These results suggest that, for these experimental conditions, the thermo-mechanical nature of pulse laser damage may yield a small, perhaps 5-10%, advantage over purely thermal cw damage. An estimate of the time

required for a cw beam of comparable average intensity (~ $6kW/cm^2$) to bring 0.016 in. thick aluminum to liquidus temperature yields a value of ~ 0.63 sec. The observed pulsed burn-through time was in the range of 0.50 - 0.58 sec.

C. Ablation Rates - Dielectrics

Ablation rates or mass-removal rates were measured for two dielectric materials, fused silica and plexiglas. The ablation rate is defined simply as the total mass loss (determined from measurements before and after irradiation) divided by the total incident energy. The results of the measurements which are shown in Table 1 are in good agreement with previously measured values.

The ablation rate for plexiglas quoted in Reference 8 is also shown for comparison. The measured value of the ablation rate for fused silica is much less than that of plexiglas. This would be expected from a comparison of the heats of vaporization for the two materials.

IV. CONCLUSIONS

Upon igniting a surface plasma, enhanced thermal coupling was observed for the aluminum and stainless steel targets. After passing through a maximum, the coupling decreased with increasing fluence and approached the cw value in the range of 40 - 50 J/cm^2. For the titanium targets, no enhancement over accepted cw values was observed; the existence of a surface plasma served only to decouple the laser radiation from the target.

The multipulse coupling measured with Humdinger, Sr., was consistently less than the single-pulse values measured by Marcus with the Lincoln Laboratory 500 J stable resonator laser. There are strong indications from the fast

TABLE I

MEASURED ABLATION RATES FOR FUSED SILICA AND PLEXIGLAS. THE RESULTS FOR PLEXIGLAS ARE COMPARED TO THOSE REPORTED IN REFERENCE 8.

Material	Intensity (MW/cm^2)	Ablation Rate (g/kJ)	Ablation Rate (Ref. 8) (g/kJ)
Plexiglas	3.8	0.24 ± .03	0.2
	0.9	0.30 ± .05	0.3
Fused Silica	2.9	0.018 ± .004	———
	0.9	negligible	

thermocouple data that differences in the pulse shape of the laser may be largely responsible for the reduced thermal coupling measured with Humdinger, Sr. A series of experiments is being planned to investigate in detail the effect of pulse shape and pulse length on the enhanced thermal coupling to metals. These measurements will utilize the Lincoln Laboratory 500 J laser into which variable pulse-forming-networks have been installed.

Measurements of the damage to the aluminum structural member indicate that for the range of experimental conditions used in this experiment the thermo-mechanical nature of pulsed laser-induced damage may yield a 5-10% advantage over purely thermal cw laser-induced damage.

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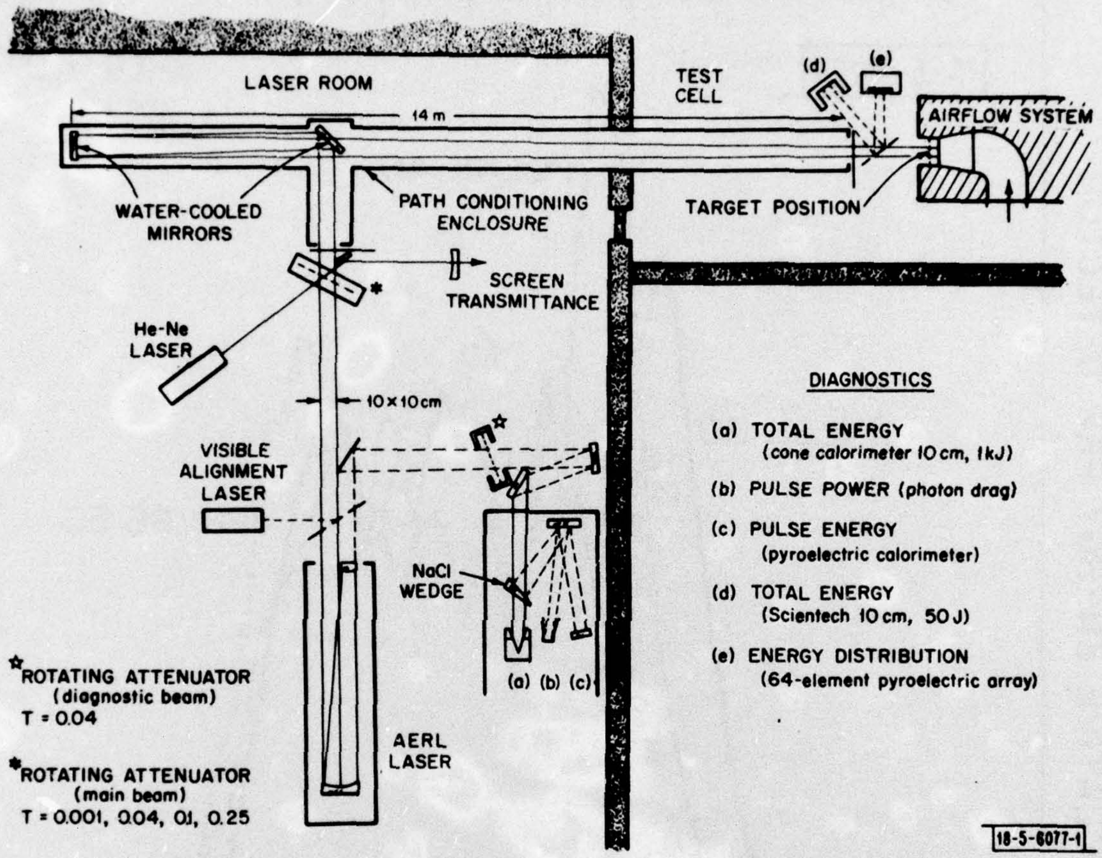

Fig. 1. Experimental arrangement for AVCO Humdinger, Sr., surface effects experiments.

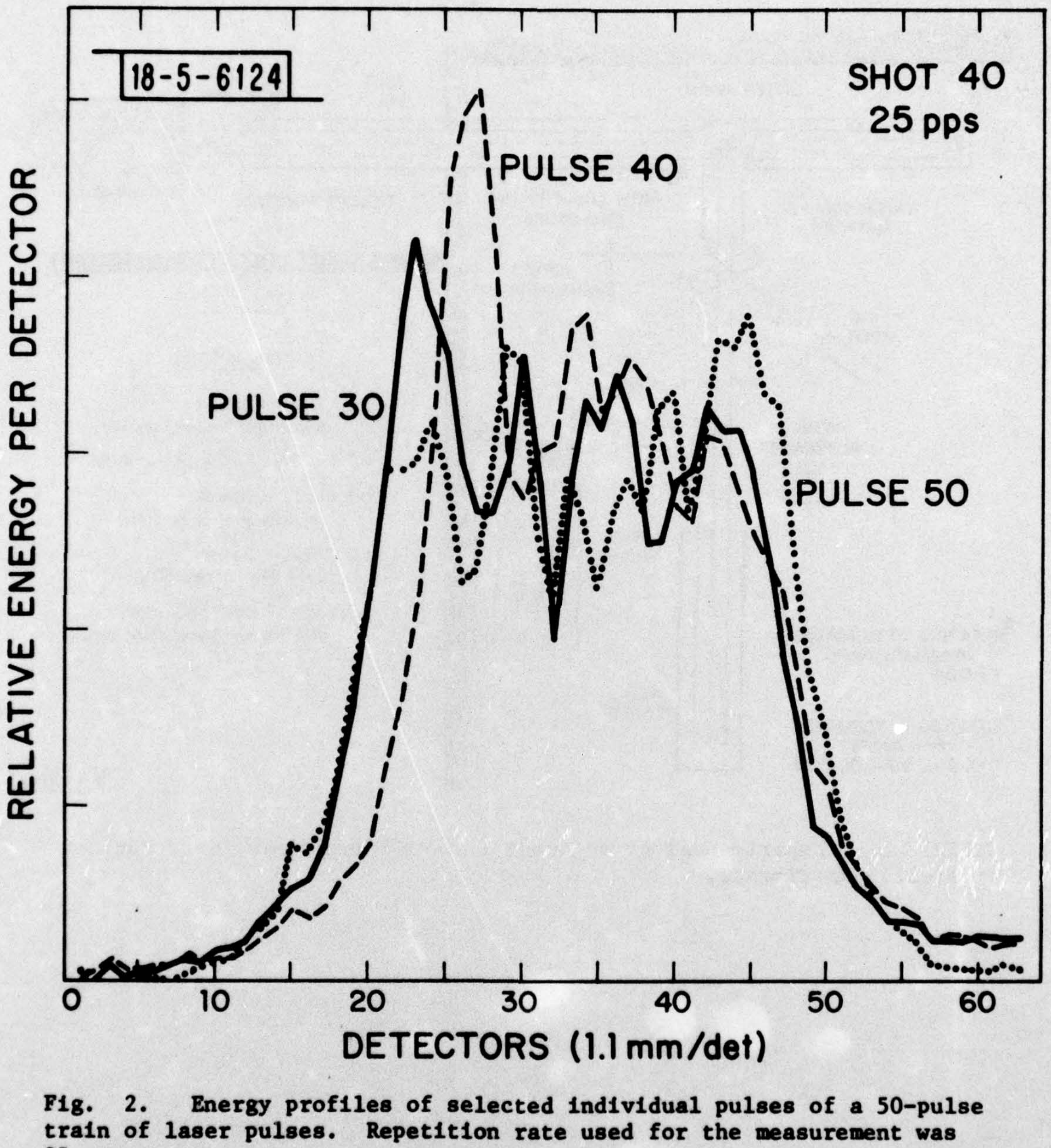

Fig. 2. Energy profiles of selected individual pulses of a 50-pulse train of laser pulses. Repetition rate used for the measurement was 25 pps.

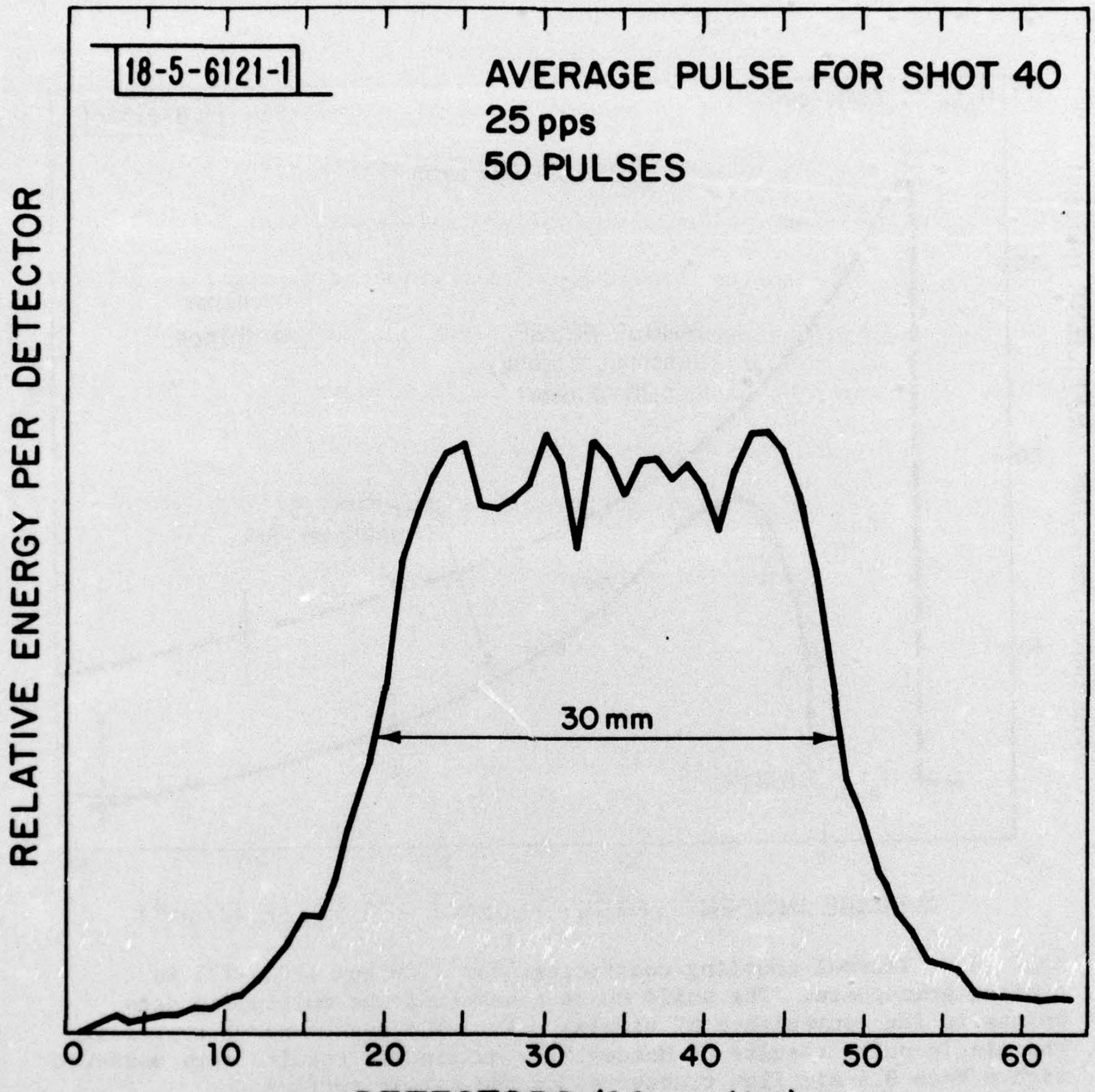

Fig. 3. Average beam profile for the pulse train shown in Figure 2. Measurements in two dimensions (horizontal and vertical slices through the beam) show that the spot reasonably approximates a flat-top distribution with full-width at half-maximum dimensions of (30±3) x (30±3) mm^2.

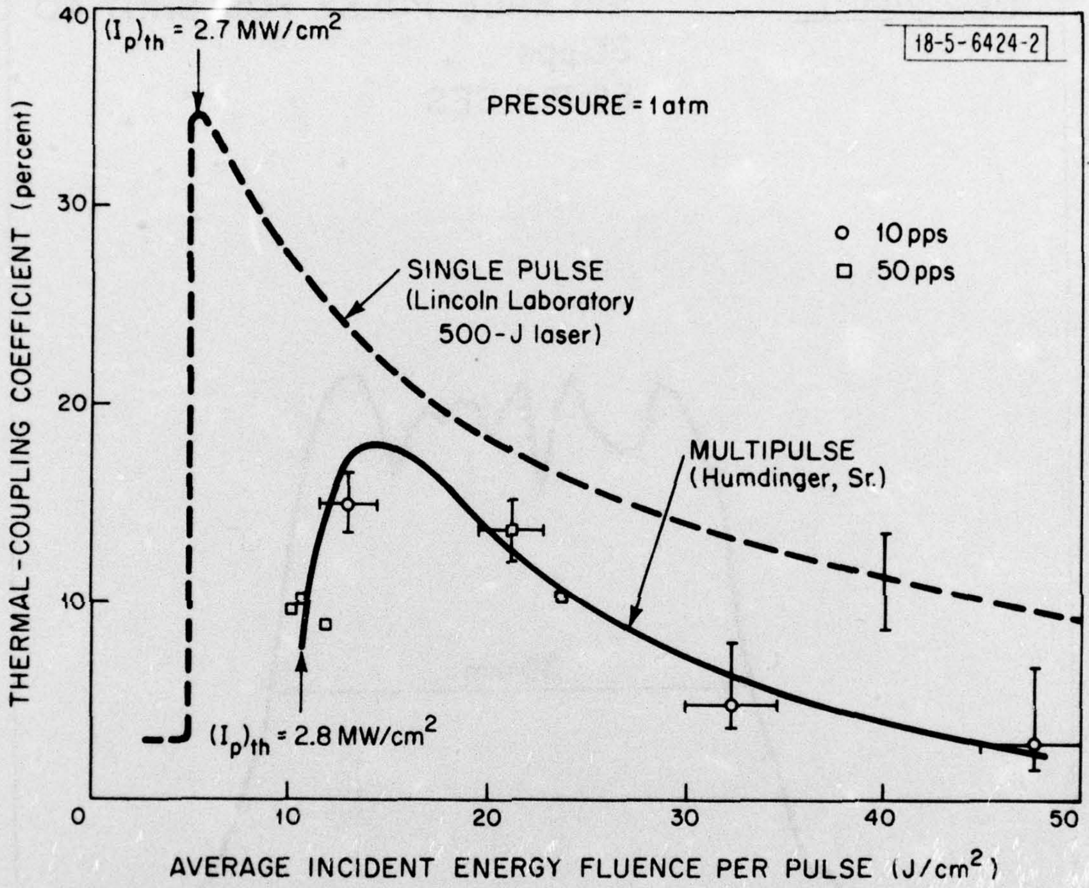

Fig. 4. Thermal coupling coefficient for aluminum (2024-T3) in ambient atmosphere. The solid curve connecting the multipulse data points is for convenience of viewing only. The dashed curve represents the single-pulse results of Marcus.[4,5] Multipulse results were measured with a Mach 0.4 air flow transverse to the target surface.

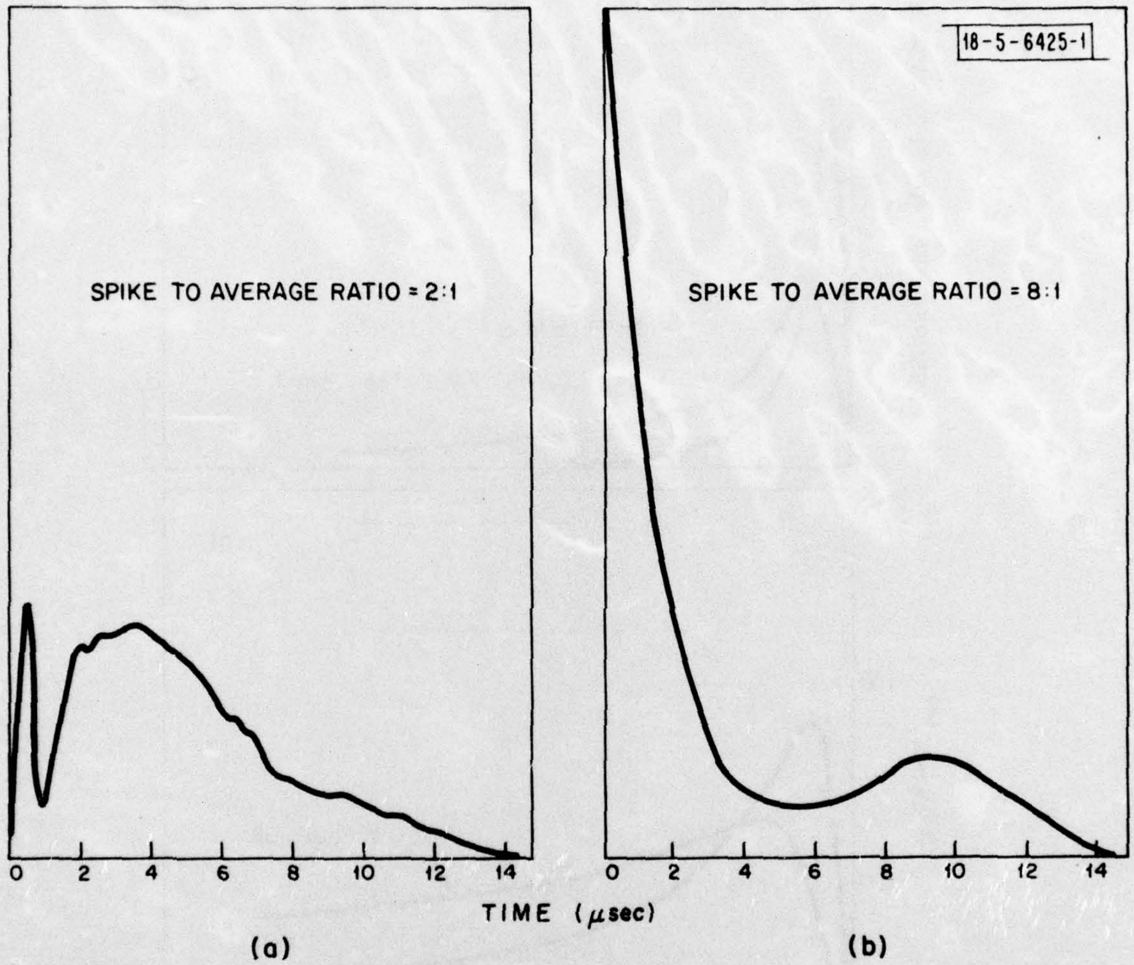

Fig. 5. Typical pulse shapes for (a) Humdinger, Sr., and (b) the Lincoln Laboratory 500 J stable cavity laser.

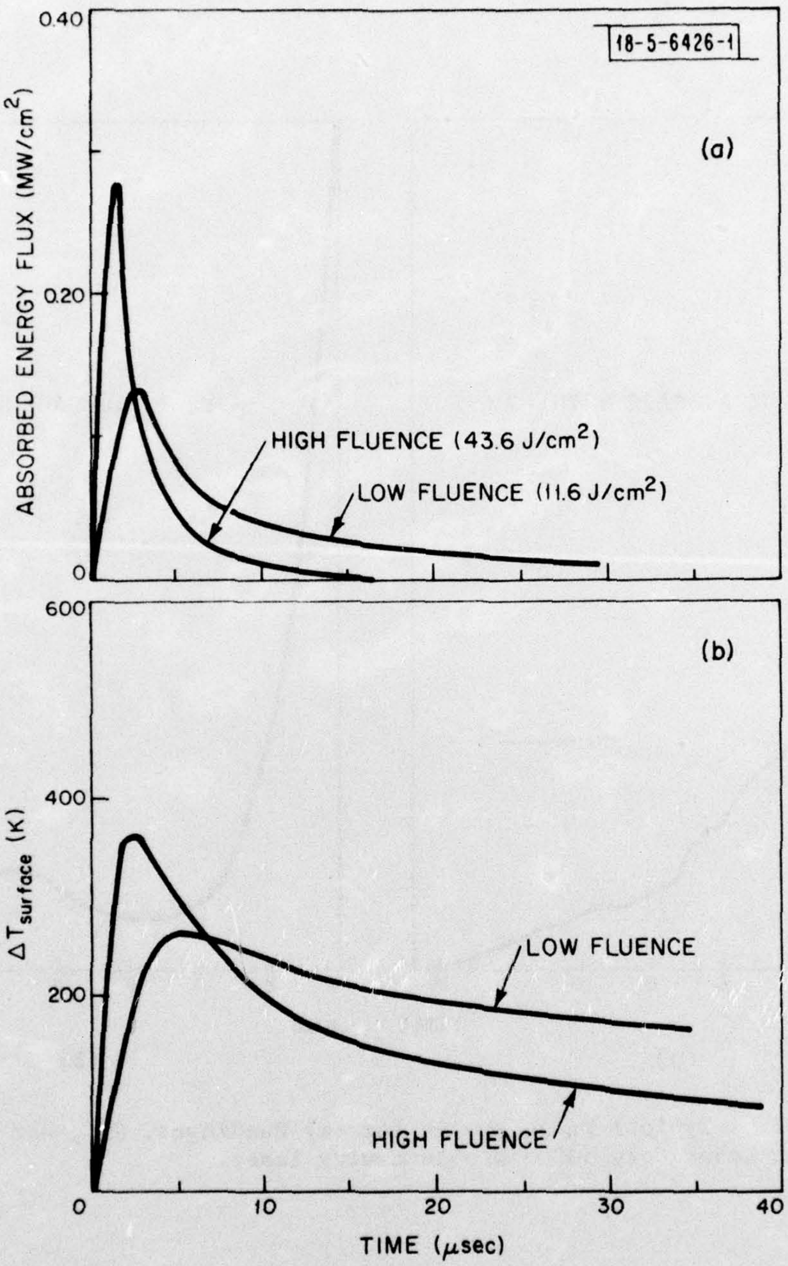

Fig. 6. Time-resolved change in (a) surface temperature and (b) absorbed energy flux for front-surface-thermocoupled copper targets. Data are presented for two fluences, 11.6 and 43.6 J/cm^2.

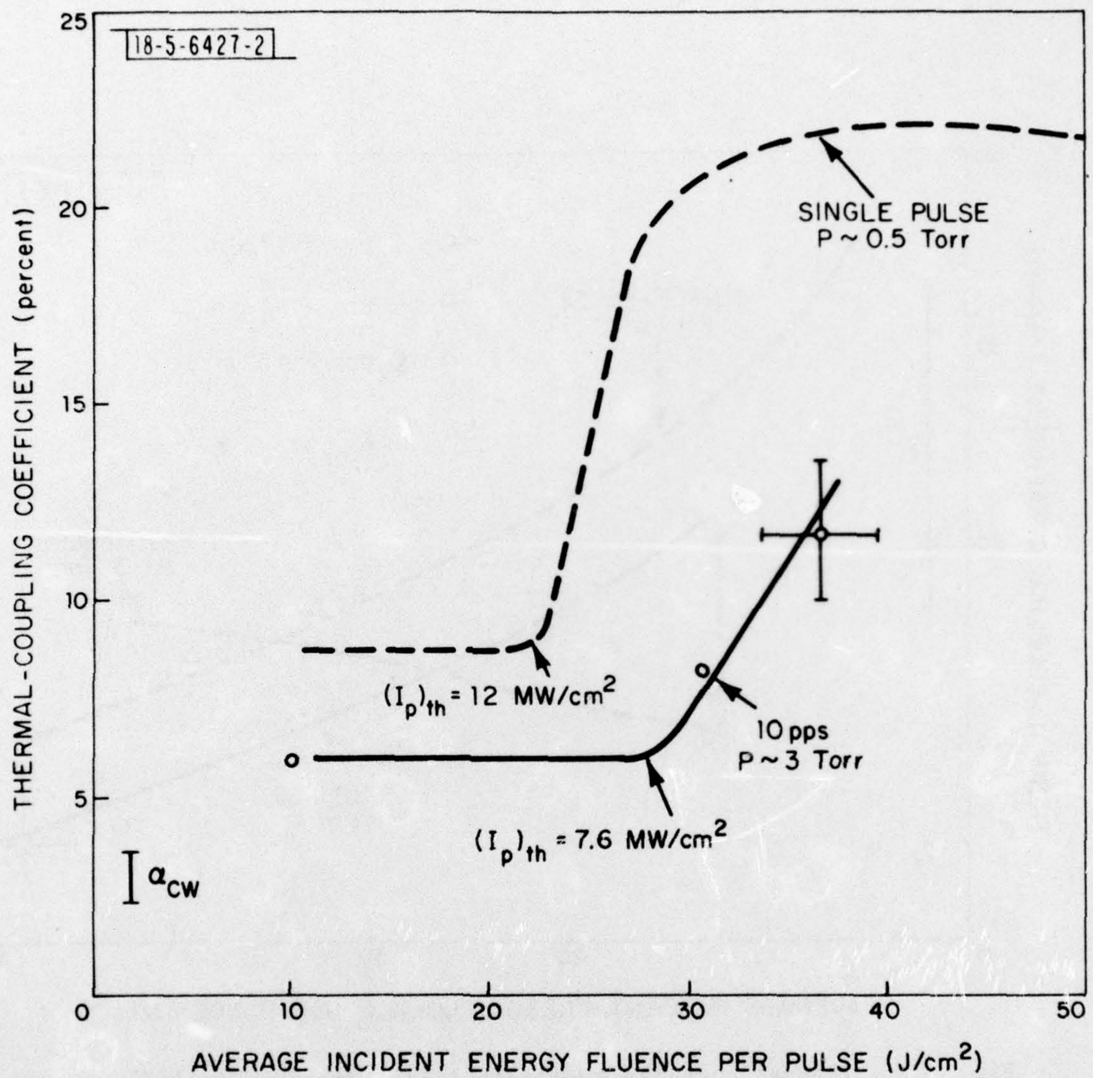

Fig. 7. Thermal coupling coefficient for aluminum (2024-T3) measured at ambient pressure of 3 torr (solid curve). The dashed curve represents the single-pulse results of Marcus[4,5] measured at P ≈ 0.5 torr.

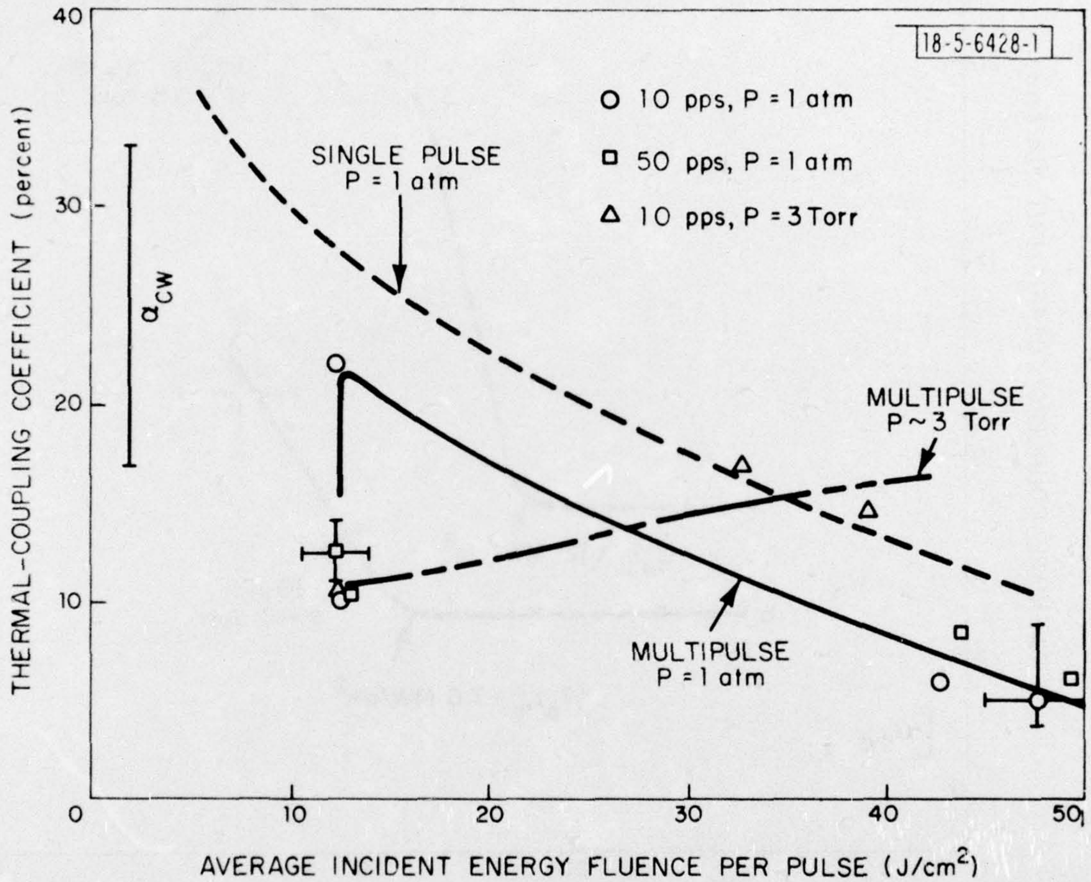

Fig. 8. Thermal coupling coefficient for titanium (6Al-4V). Multipulse ambient atmosphere results (connected by the solid curve for viewing convenience) were measured with a Mach 0.4 air flow transverse to the target surface. The dashed curve represents the single-pulse results of Marcus.[4,5] Low-pressure multipulse results are also shown and connected by the broken curve for viewing purposes.

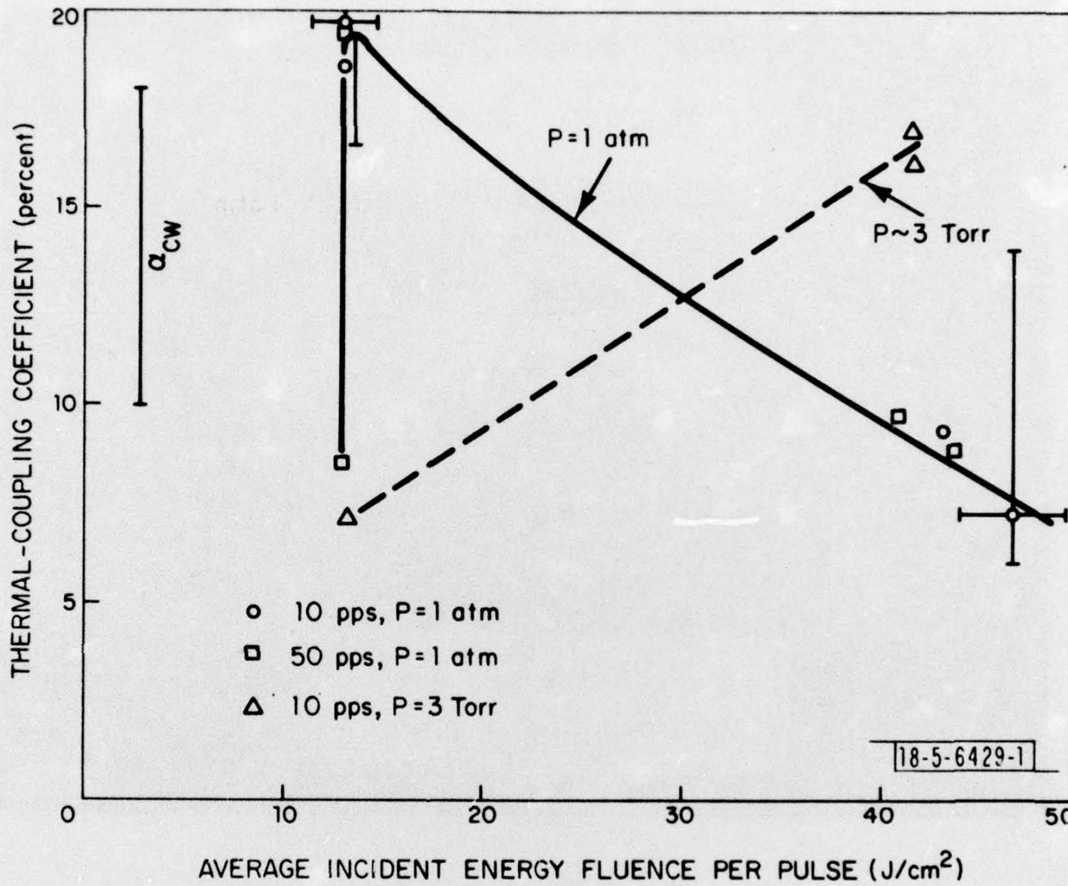

Fig. 9. Thermal coupling coefficient for stainless steel (304). Ambient atmosphere measurements (solid curve) were made with a Mach 0.4 air flow transverse to the target surface. Low-pressure results (dashed curve) are also shown. The curves in both cases are for viewing purposes only.

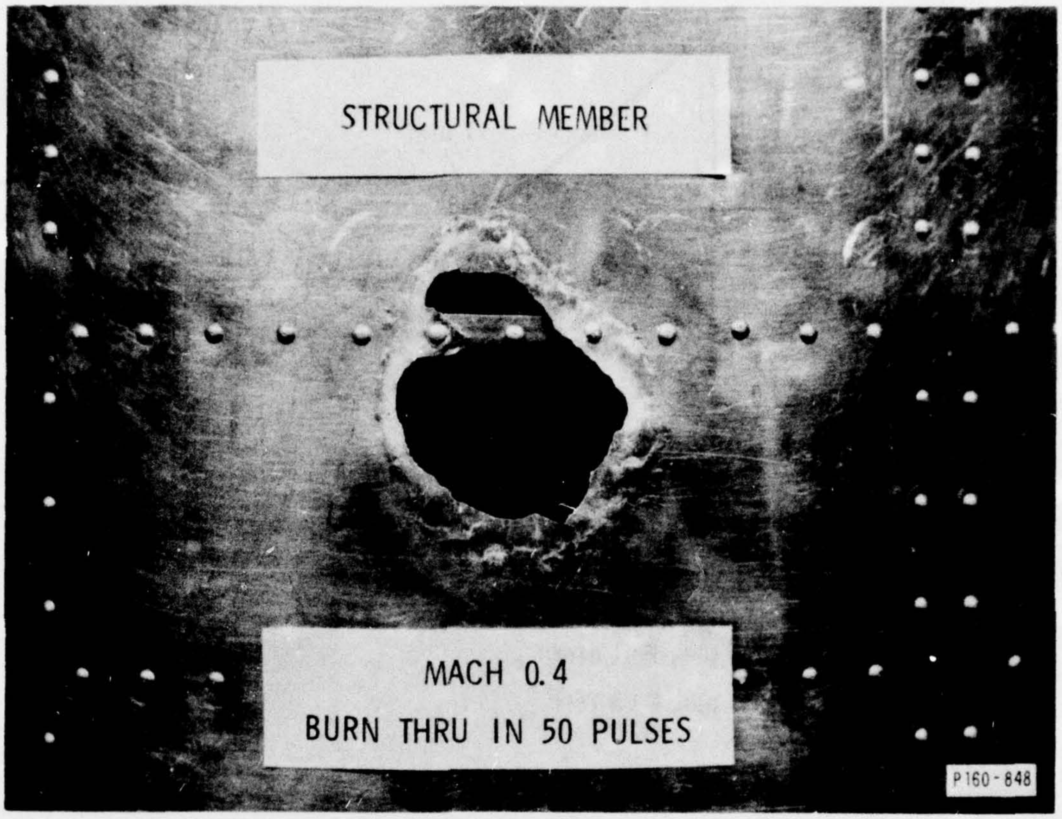

Fig. 10. Damage to structural member produced with Mach 0.4 air flow transverse to surface. The average pulse fluence was ~ 58 J/cm^2 and the repetition was 100 pps.

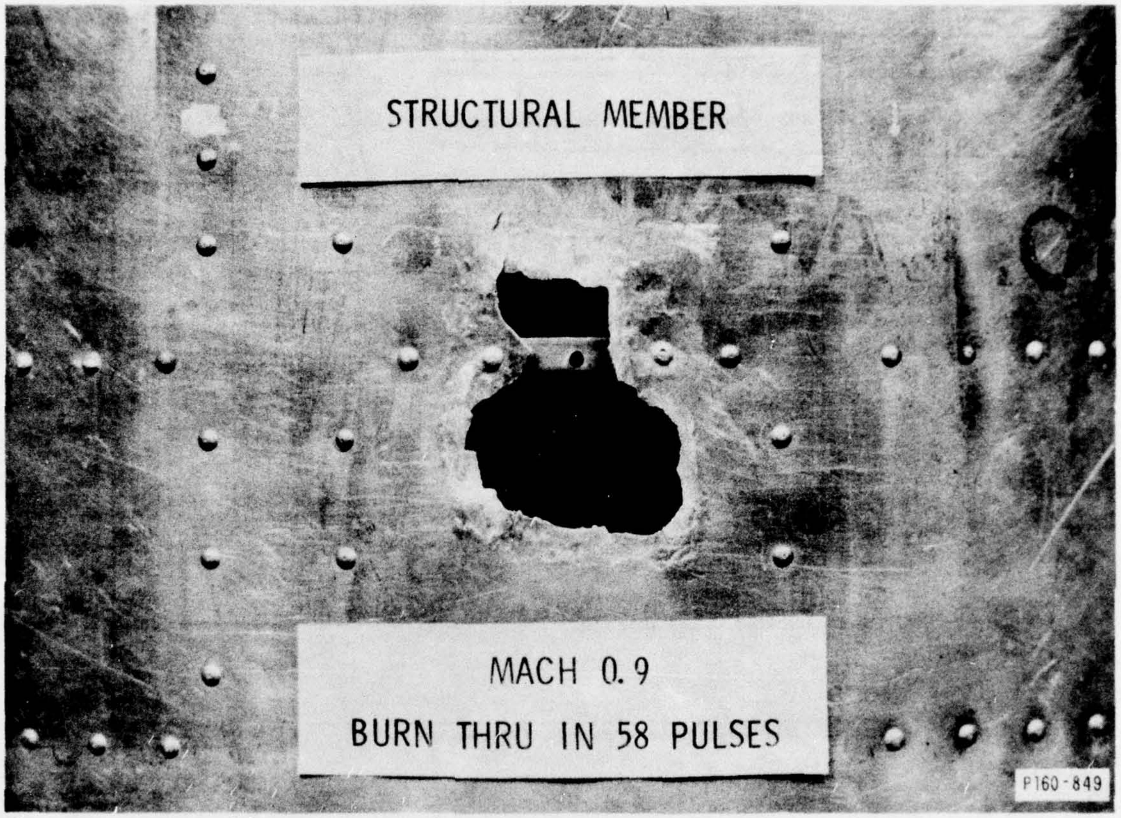

Fig. 11. Damage to structural member produced with Mach 0.9 air flow transverse to surface. The irradiation conditions were the same as given for Figure 10.

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14 LTP-34

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Thermal coupling of CO_2 laser energy to metal surfaces of aluminum, titanium, stainless steel and copper has been measured under large-spot, repetitively pulsed conditions using the AVCO Humdinger, Sr., laser. Measurements were made at atmospheric pressure with a Mach 0.4 air flow transverse to the target surface and in a low-pressure environment of ~3 torr. The multipulse coupling measured with Humdinger, Sr., is consistently less than previous measurements of single-pulse and small-spot multipulse coupling measured at other laser facilities. Time-resolved measurements of the energy deposition indicate that the differences in the various sets of coupling data may be due to pulse shape effects.

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